UNDERWATER EVALUATION OF PIEZOCOMPOSITE PANELS AS ACTIVE SURFACES

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ABSTRACT

A new class of composite materials designated as the 1-3 piezocomposite is being investigated for potential use in underwater smart material structures. In-water acoustical properties of new 1-3 composite panels were examined experimentally as a function of temperature, pressure and frequency. The measured transmitting voltage response (TVR) showed the existence of parasitic modes in the composite panel in addition to the expected thickness mode. The effect of underwater explosive shock on the TVR showed no detrimental effects in mechanical structure or acoustical performance of the piezocomposite panel. The free-field voltage sensitivity (FFVS) was constant at -185 dB referenced to 1 volt per micropascal over the testing frequency range. Linearity with electrical drive level and pressure stability of the 1-3 piezocomposites have also been established with the present choice of ceramic-polymer components. These results demonstrated that this new material is potentially useful for applications of both large-area actuators and sensors in forming active surfaces of new smart structures.

Key words: Piezoelectric, composite, underwater acoustics, actuator, sensors.

1. INTRODUCTION

In recent years, there has been an increasing emphasis on the development of smart materials and structures. For such a structure, sensors are required to detect the incoming signals, and actuators are needed to bring forth proper reactions to the signal. Common practices are to use piezoelectric ceramics of lead-zirconate-titanate (PZT) compositions for sensor and actuator applications in smart structures[1,2]. However, these bulk ceramics are dense, heavy and of limited size and shape. When large area coverage is required, they are rather difficult to apply. Furthermore, in some applications involving the coverage of a large surface, the sensors detect the signals in a hydrostatic mode. The piezoelectric voltage coefficient in this mode is related to the other coefficients through the following equation:

$$g_h = g_{33} + g_{31} + g_{32}$$

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Unfortunately, in PZT ceramics both the coefficients g_{31} and g_{32} have magnitudes nearly equal to half of that of g_{33} but are of a different sign[3]. This results in a very small g_h, or a very poor hydrostatic mode response[4].

Early research efforts at the Pennsylvania State University's Materials Research Laboratory led to the development of a large variety of piezoelectric composite materials that consist of a ceramic and a polymeric phase with different connectivities[5]. The connectivity in one, two or three dimensions in a composite is designated as 1, 2 or 3. Therefore, a piezocomposite consisting of thin piezoelectric ceramic rods aligned in parallel and embedded in a polymeric resin is called a "1-3" composite. The ceramic rods are connected in only one direction, namely the poled direction of the material, having a connectivity of "1." On the other hand, the polymer phase is connected in all three dimensions, having a connectivity of "3." Figure 1 shows a schematic of the 1-3 piezocomposite concept.

In recent years, this type of piezoelectric composite material was investigated for applications in large-area hydrophones and as high-frequency underwater imaging transducers[6,7]. It has now been selected for inclusion in the ARPA Smart Materials and Structures Program for further development so that the material can be applied in the fabrication of large active surfaces of new smart structures. The emphasis of this development is on the new low-cost fabrication method for the piezocomposites. In the past, 1-3 piezocomposite materials were traditionally fabricated by using a dice-and-fill method[8]. This method was adequate for the preparation of small samples required in ultrasonic medical imaging applications. However, it is not only too labor intensive and, therefore, costly to meet the need of large area coverage in Naval applications, but too difficult to maintain material uniformity in large sheets. At Materials Systems Inc. (MSI, Littleton, MA) an injection molding technique was developed to make 1-3 composite preforms of manageable size. The individual preform parts were then assembled into large panels of 1-3 piezocomposite by using a polyurethane resin for encapsulation. In this paper, the basic configurations of large 1-3 panel structures developed are first described. The effects of temperature, pressure and underwater explosive shock on the in-water acoustic performance of the panels as large-area sensors and actuators in a smart structure were examined, and the experimental results are reported here.

2. PANEL CONFIGURATION

The basic configuration of the MSI fabrication[9] using an injection molding technique is a ceramic preform 50 mm x 50 mm in size, containing a 19 x 19 array of 361 rods. Each rod is 1.1 mm in diameter and about 7.9 mm in height. The ceramic of present choice is the PZT-5H composition from Morgan Matroc Inc. Ceramic powder was thoroughly mixed with a binder to form a viscous mixture. During the injection molding process, the mixture was forced into a cooled mold to form a net shape green part. This part was subsequently heated in air for the removal of the organic binder. Sintering then took place at 1250°C for one hour with controlled atmosphere to optimize the PZT piezoelectric properties. The preform was then contact-poled under high electric field. Individual preform parts were assembled to the size of a desirable transducer panel and ground flat and parallel, usually to 6.3 mm thick. The panel was subsequently encapsulated by using castable resins such as polyurethane. After proper cure, the panel surface was finished and permanent electrodes were applied for attaching the wires. The final 1-3 pizocomposite panel contained approximately 15% volume fraction of PZT with a nominal dielectric constant of 480 and a density of 1.8 g/cm^3. Presently, the material is available from MSI under the trade name "SonoPanel 5H."

3. EXPERIMENTAL METHODS

Underwater acoustical properties of new 1-3 piezocomposite panels including the transmitting voltage response (TVR) and the free-field voltage sensitivity (FFVS) were determined in both the USRD Lake Facility and the high pressure Anechoic Tank Facility (ATF) in Orlando, Florida. Generally, the TVR provides information on the behavior of an electroacoustic transducer used in active mode for sound transmission. It is the ratio of the sound pressure apparent at a distance of one meter in a specified direction from the effective acoustic center of the transducer to the signal voltage applied across the electrical input terminals. TVR is reported in decibels referenced to one micropascal per volt. On the other hand, FFVS gives the sensitivity of an electroacoustic transducer used for sound reception. This quantity is the ratio of the output open-circuit voltage to the free-field sound pressure in the undisturbed plane progressive wave, and is reported in decibels referenced to one volt per micropascal. A detailed description of the underwater acoustic calibration methods can be found in the reference by Bobber[10]. Calibration in the ATF was carried out at the discrete temperatures of 4 and 22°C up to a maximum pressure of 7 MPa. The frequency coverage of the measurements was from 100 Hz to 400 kHz. Effects of underwater explosive shock on the performance of the piezocomposite samples were evaluated by using the conical shock tube developed at USRD[11]. In this case a maximum shock-front pressure pulse of over 15 MPa was achieved with a rise time of approximately 10 microseconds. The acoustical performance of a transducer before and after the shock exposure was evaluated for comparison in order to assess the effect of such a shock on the performance of the panel.

4. MEASUREMENT RESULTS

Figure 2 shows the transmitting voltage response (TVR) of a sample panel in dB referenced to one micropascal per volt. The primary thickness mode resonance appeared at about 320 kHz which is as expected from theoretical calculation. In addition, one also finds a mode at 100 kHz, the origin of which is not yet clear, but is believed to be closely related to the two-phase nature of this composite material. The different acoustic velocities in the ceramic and in the polymer could be a major factor causing this to occur. The geometrical design of the material, such as the rod-to-rod spacing and the aspect ratio of individual rods, is also an important factor. This mode can be shown to have an effective coupling coefficient of about 0.35 or more. Therefore, for actuator applications of the 1-3 piezocomposite panels one may take advantage of this strong low frequency coupling in addition to the conventional thickness mode of the panel. The increase in TVR with frequency is slightly greater than the normal 12 dB per octave variation. This indicates that the overall panel displacement is somewhat different from that of an idealized point source. If one considers the large size of the piezocomposite panel, this difference is not totally unexpected. In-plane modes of the panel would provide the overall panel with a certain displacement profile. Nevertheless, it is clear that this strong coupling behavior around 100 kHz results in an improved acoustic bandwidth. When increasing the electrical drive level from about 0.16 kV/cm to over 1.1 kV/cm, the source level increases linearly with the drive. This linearity with the electrical drive level is very important for actuator applications. The effect of an underwater explosive shock on the TVR of the 1-3 composite panel is also shown in Fig. 2, suggesting only a one dB loss in TVR. Furthermore, the panel shows no physical damages due to exposure to two consecutive shocks.

The effect of pressure cycling on the TVR of 1-3 composite panels is demonstrated in Fig. 3. When measured at 22°C, the TVR showed a few dB variations due to the change in pressure when pressure was stepped up from the ambient to 3.5 MPa and 6.9 MPa, then reduced to 3.5 MPa before returning the system to the ambient pressure. It seems apparent that the extreme high pressure of 6.9 MPa had a slight effect in degrading the transmitting response. The pressure effect on the overall acoustical behavior of the panel is more clearly seen when one examines the receiving response. Fig.4

gives the free-field voltage sensitivity (FFVS) in dB referenced to one volt per micropascal. Nominally a constant FFVS at -185 dB was observed over the frequency band of the measurement. This is not only an adequate sensitivity but also ideal for broadband reception of signals from a few kHz to 100 kHz. When pressure cycling from the ambient pressure to a maximum of 6.9 MPa was carried out at 22°C, the deterioration of the acoustic performance was found to be of the order of 3 dB. However, after the release of this pressure, the material seemed to recover fully with no change from the original FFVS characteristics. Unfortunately, when tested at 4°C, the sensitivity decreased by as much as 10 dB. This strongly suggests that other polymeric resins should be considered for low-temperature applications in order to develop a panel that has properties stable with hydrostatic pressure at these temperatures.

5. CONCLUSION

New 1-3 piezocomposite panels have been fabricated by using a cost-effective injection molding method. In-water acoustical measurements show the presence of parasitic modes in addition to the conventional thickness mode of a plate. The present panel configuration appeared to be stable with pressure up to 6.9 MPa and is resistant to underwater explosive shock as determined from tests in a conical shock tube. The underwater acoustic performance of the panels suffers its most severe test when the composite material was exposed to high pressures at 4°C. An optimized polymer phase should improve the temperature stability of 1-3 piezocomposites for low-temperature use. In summary, 1-3 piezocomposites with high sensitivity, flat broadband response and linearity in drive appear to be promising candidates for sensor and actuator application in large active surfaces of new smart structures.

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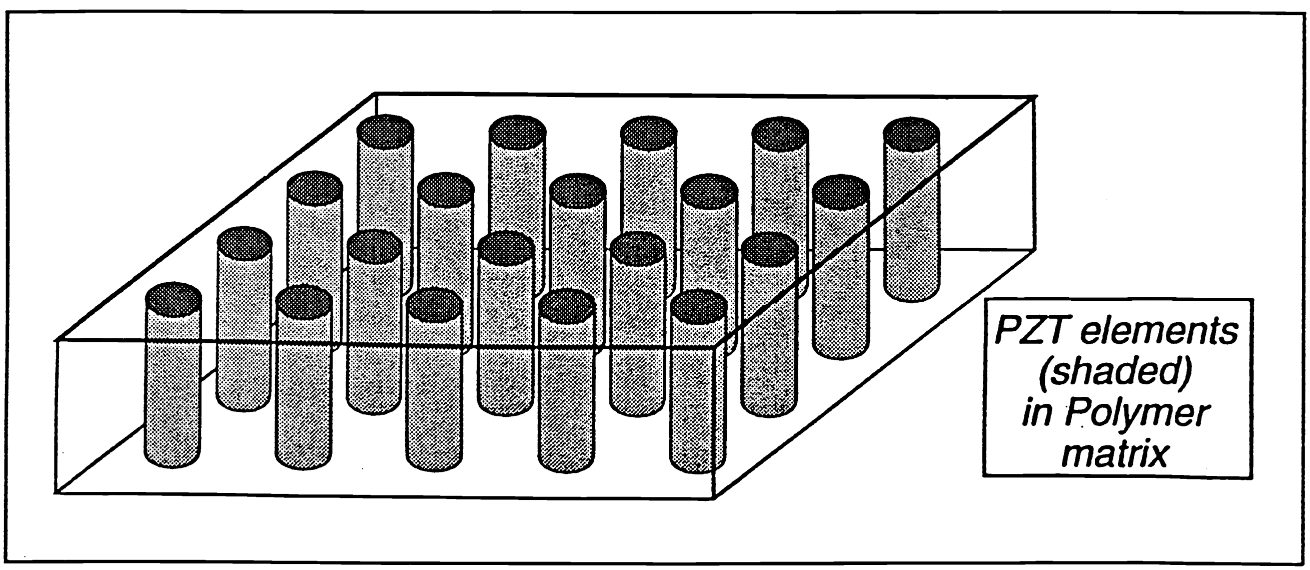

Fig. 1 - A schematic showing the configuration of 1-3 piezoelectric composite materials.

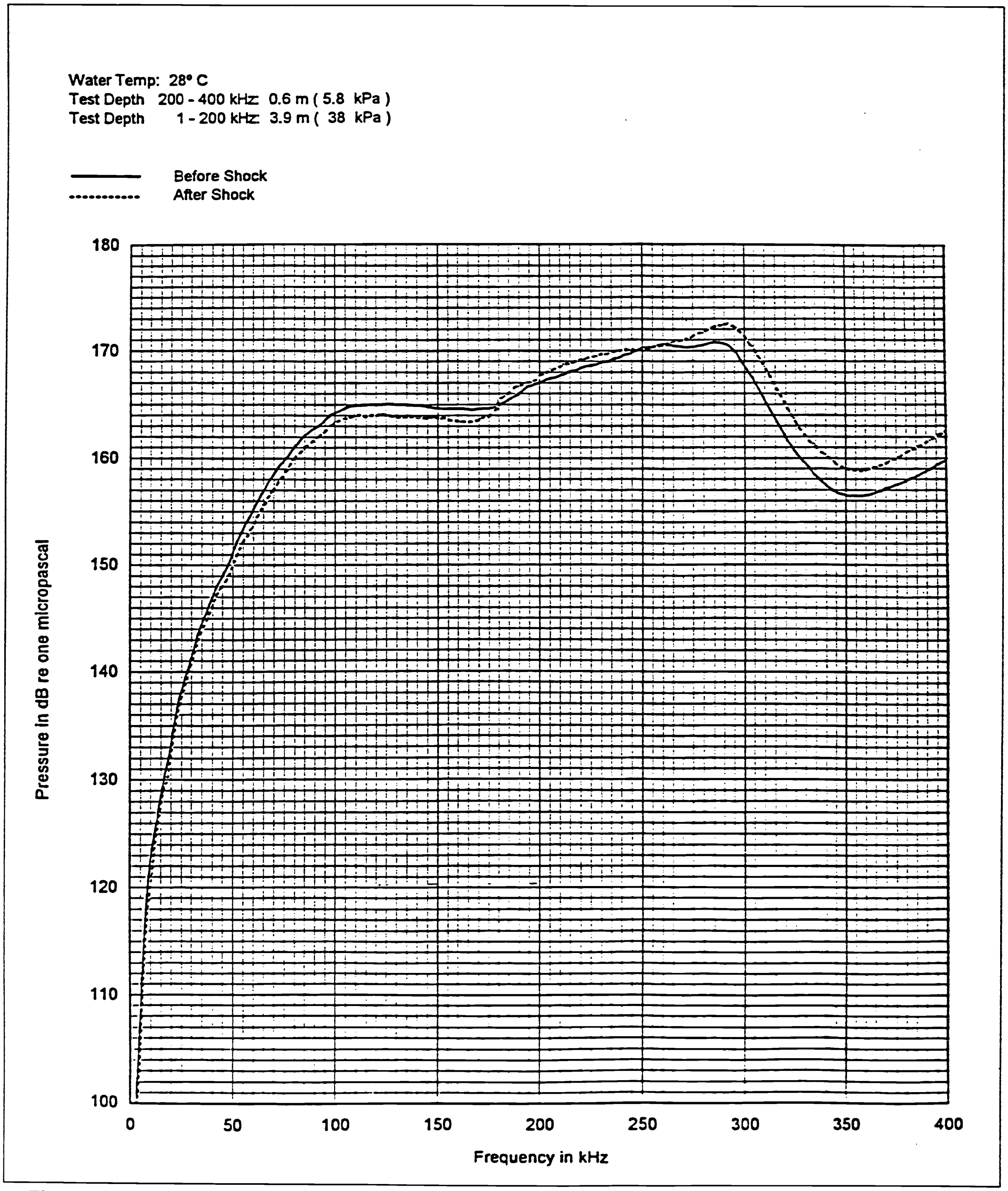

Fig. 2 - Effect of underwater explosive shock on the transmitting voltage response of a 1-3 piezocomposite panel.

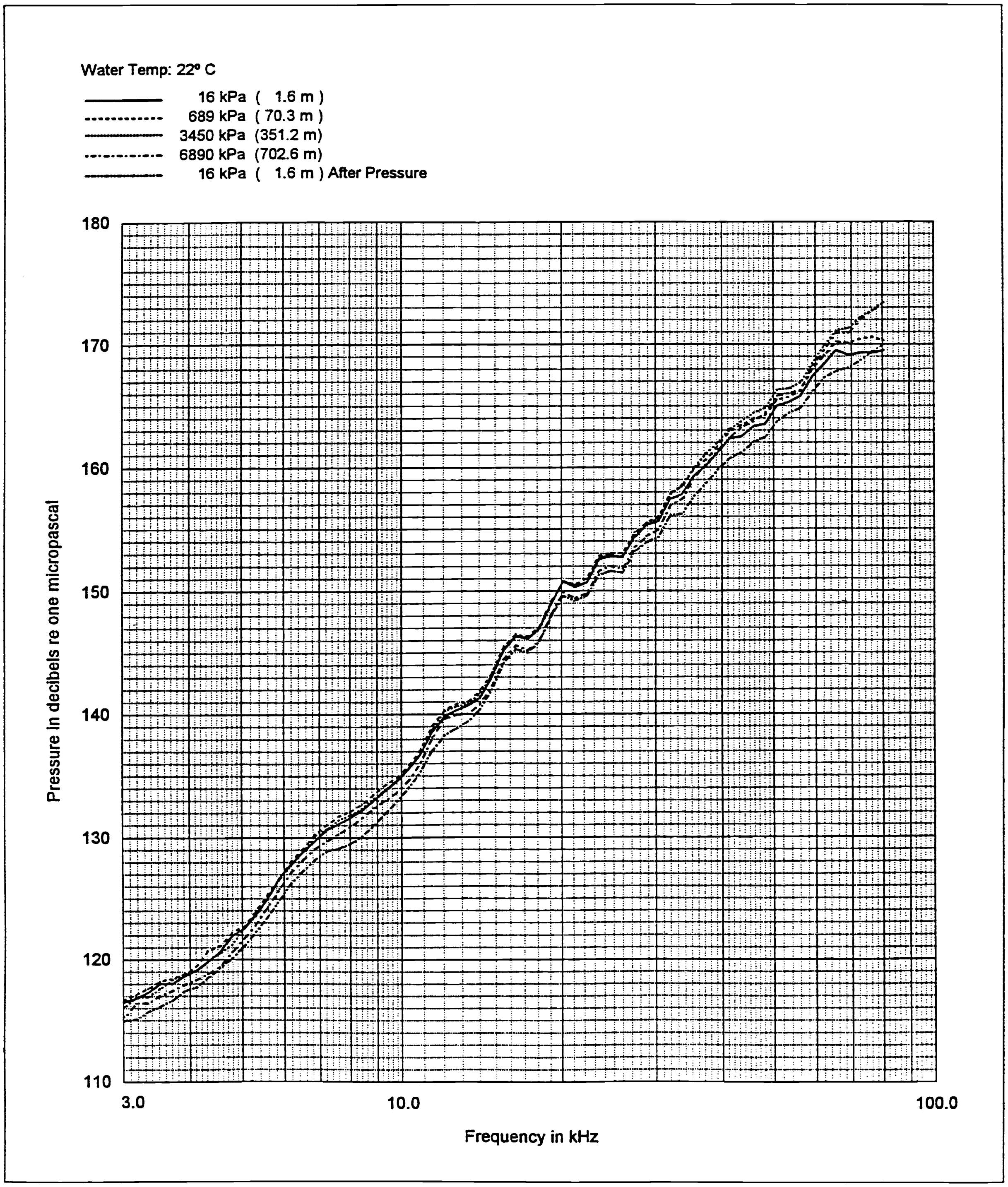

Fig. 3 - Effect of hydrostatic pressure on the transmitting voltage response of a 1-3 piezocomposite panel.

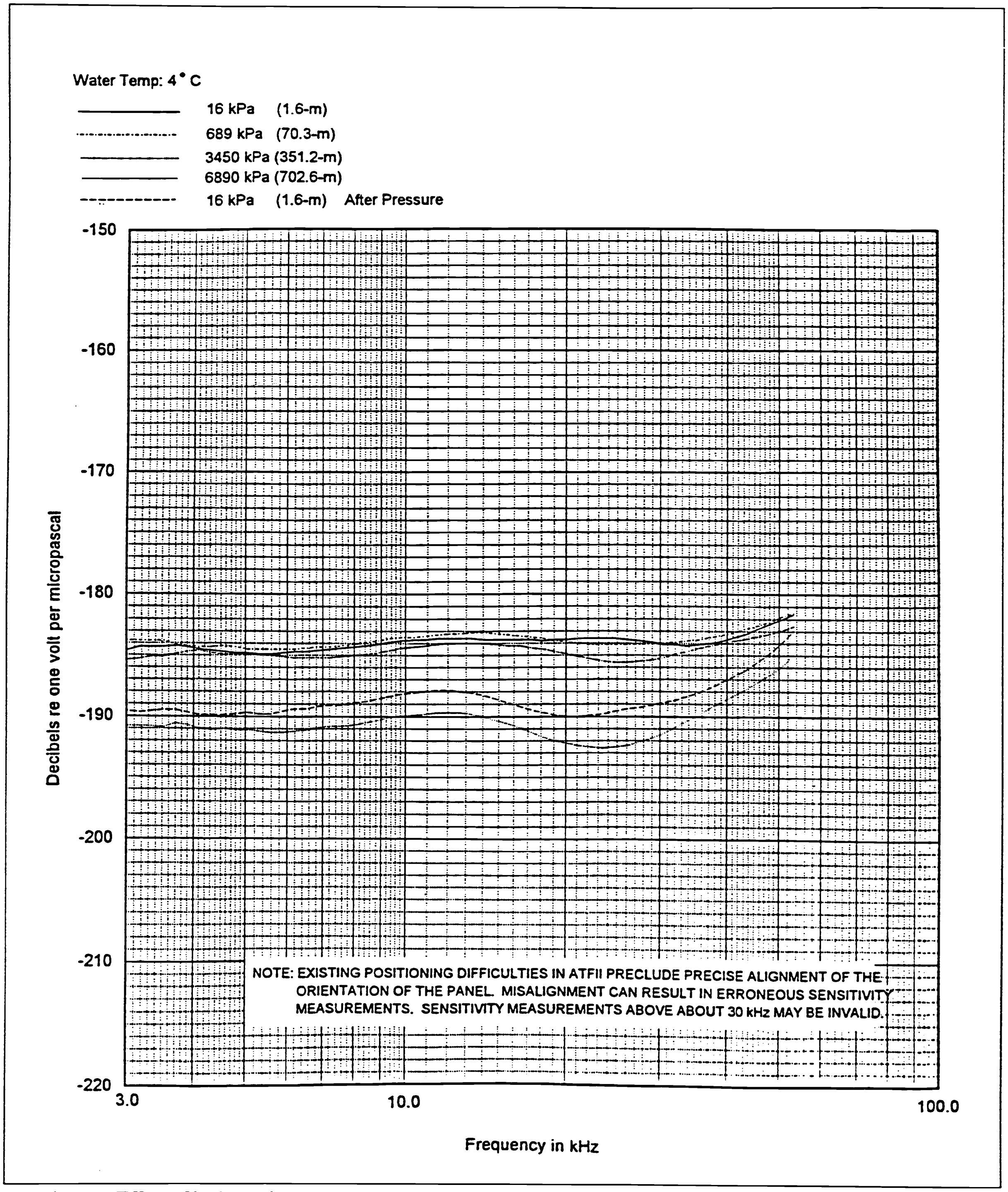

Fig. 4 - Effect of hydrostatic pressure on the free-field voltage sensitivity of a 1-3 piezocomposite panel at 4°C.

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